





- Typical risks associated with LNAPL
- Sustainable mindset
- LNAPL?
- LNAPL conceptual site model
- Case example
- Summary



#### Typical Risks Associated with LNAPL

- Direct contact with LNAPL
- Groundwater plume from dissolution
- Vapor plume from volatilization/evaporation



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# When we are worrying about thin layers...



#### Typically...

- Vapor phase has been managed or not a concern
- Groundwater plume is naturally attenuating or managed
- Managing the thin layer for typically a non-risk issue



#### Typical thin layer LNAPL management...

- When only a nuisance level of sheen or a thin layer of LNAPL remains, the recoverable portion of the LNAPL body has been removed
- The remediation approach is typically routine site visits
  - Management of low technology device (sorbent socks, passive bailers, skimmers, etc.)
  - Long-term monitoring during regular site visits.
- Will not remove the remaining LNAPL within the subsurface
- LNAPL bodies will remain in the subsurface for years, to decades and possibly even centuries, as they naturally attenuate



## Sustainable Thinking Throughout...





#### Sustainability has gone mainstream

















How to Win The War On Global Warming

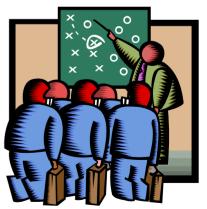
## Sustainability concerns with typical LNAPL management programs...

- As the LNAPL approaches residual levels remediation becomes
  - more difficult technically
  - more costly (>\$ per gallon removed)
  - more environmental concerns (carbon footprint)
  - safety perspective (multiple site visits)
- There comes a point that these costs exceed benefits such as the potential reduction in risk to human health



## One solution may be to demonstrate Non-Risk of remaining LNAPL

- Ground water naturally attenuating
- LNAPL body footprint is stable or shrinking
- LNAPL body drivers are minimal
- Mobility of LNAPL body is not present
- Areas of LNAPL body with potential mobility (i.e., recoverability) are minimal



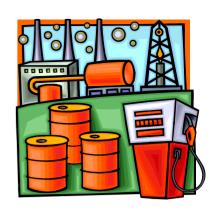


#### LNAPL 101

- NAPL → Nonaqueous Phase Liquid
  - LNAPL → Light NAPL
  - DNAPL → Dense NAPL



- Nonaqueous → do not mix with water
- Petroleum liquids in soils and ground water
- Derived from crude oil
- Common LNAPLs:
  - Fuels, Lubricants, Chemical Feed Stock





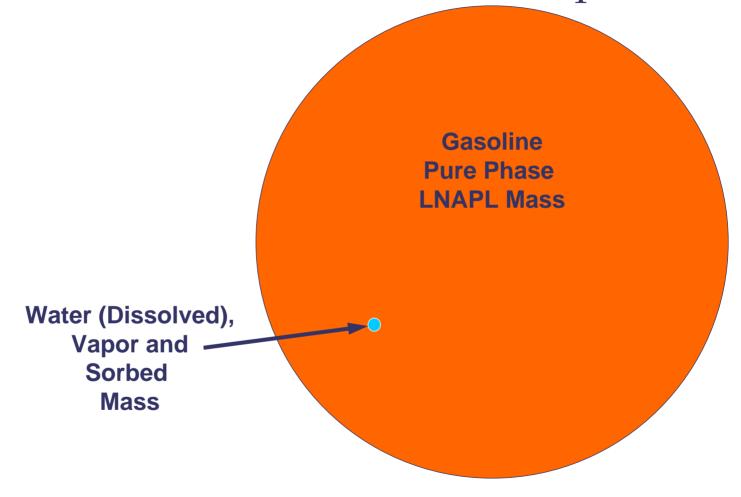
#### LNAPL 102



- Typically found at top of groundwater zones
- Water and LNAPL do not mix → immiscible
  - Share pore space which limits the mobility
- Composed of compounds of concern (COCs)
  - Dissolves at trace levels above standards
  - Solubility of COCs is low enough for natural processes to attenuate over small distances



#### LNAPL is the Usual Source of Impacts





#### Why Concerned with LNAPL?

- Longer term concentrated chemical source mass
- Potential risks emanate from "source"
- Cleanups either manage pathways / target source
  - Most recovery actions leave residual mass
  - Actions and decisions are hinged on the...

LNAPL Conceptual Site Model



#### ASTM E 2531-06

- Development of CSM for remediation strategies for LNAPL released to the subsurface (i.e., LCSM)
- Tiered process with higher tiers for more difficult sites
- Provides framework for developing a LCSM
  - Guide for remediation metrics
  - Remediation strategy should be consistent with site objectives
  - Movement of LNAPL should be measured at a scale pertinent to LNAPL site objectives

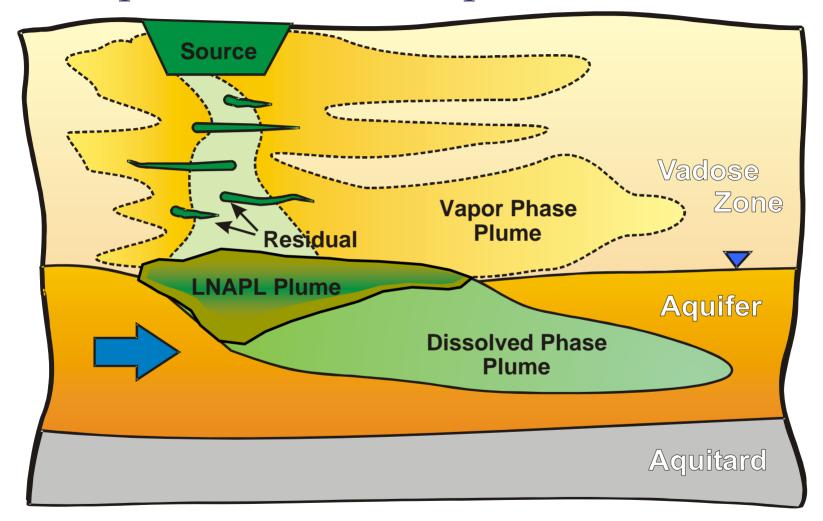


Designation: E 2531 - 06

Standard Guide for Development of Conceptual Site Models and Remediation Strategies for Light Nonaqueous-Phase Liquids Released to the Subsurface<sup>1</sup>

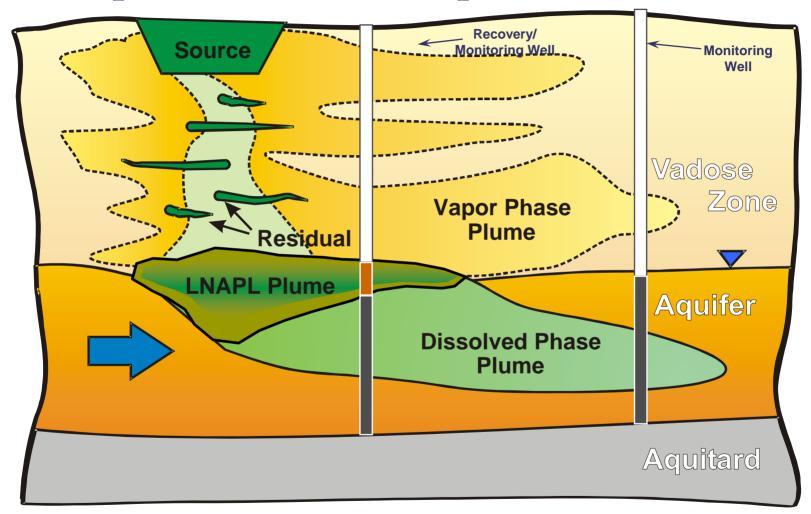


## Example LNAPL Conceptual Site Model





#### Example LNAPL Conceptual Site Model





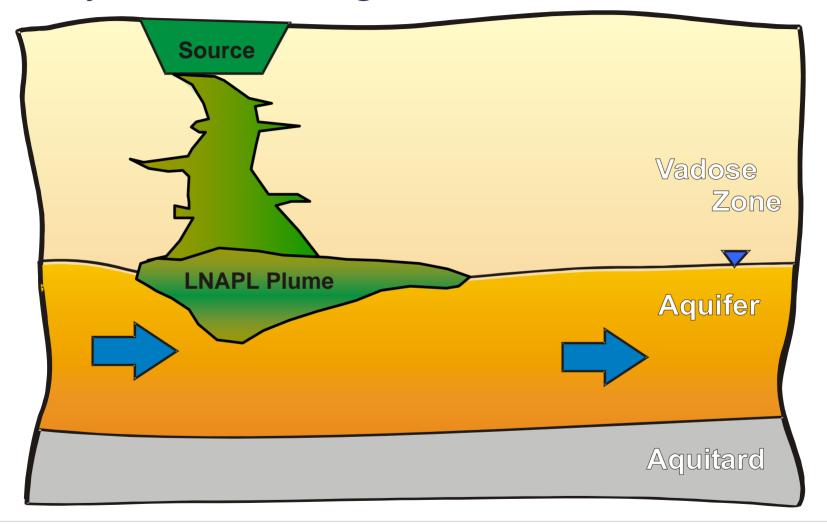
#### Are LNAPL bodies stable?



- During a release... No
- Soon after the release... Potentially
- Longer period after the release... Likely
- Thin layers... Yes

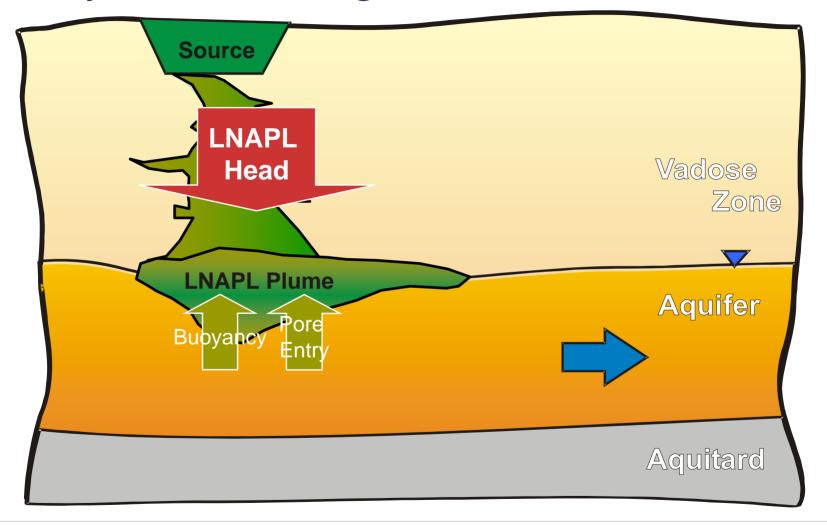


## Early Release - High Head



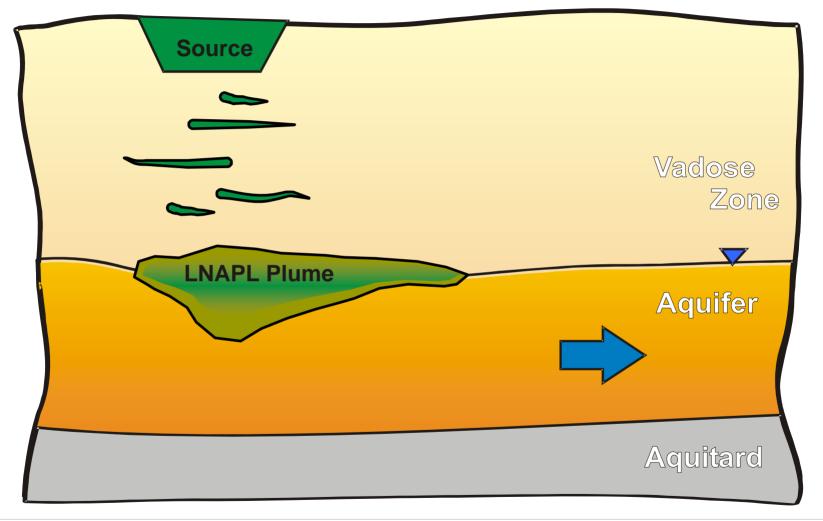


## Early Release - High Head



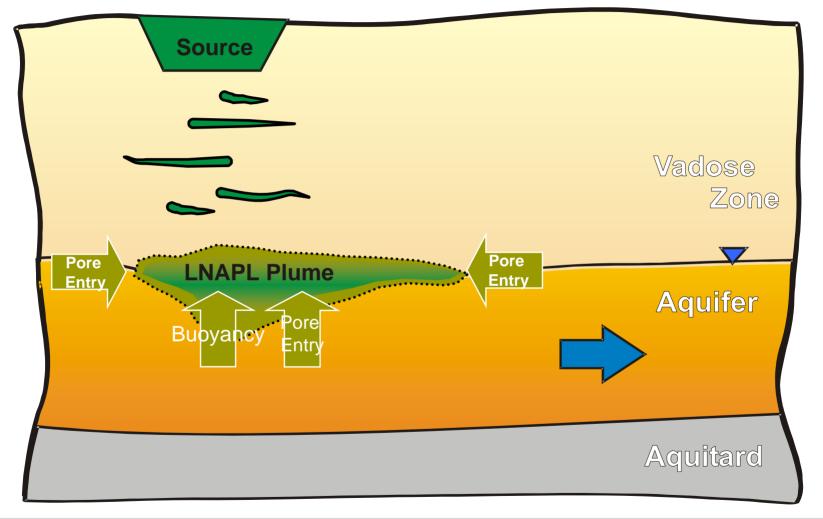


## Longer time after Release - Head gone



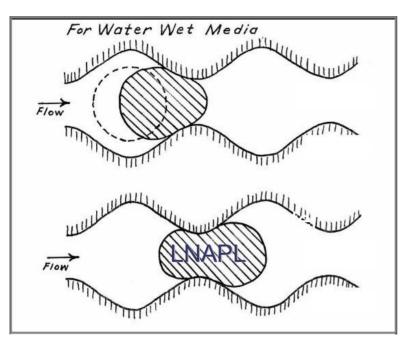


## Longer time after Release - Head gone



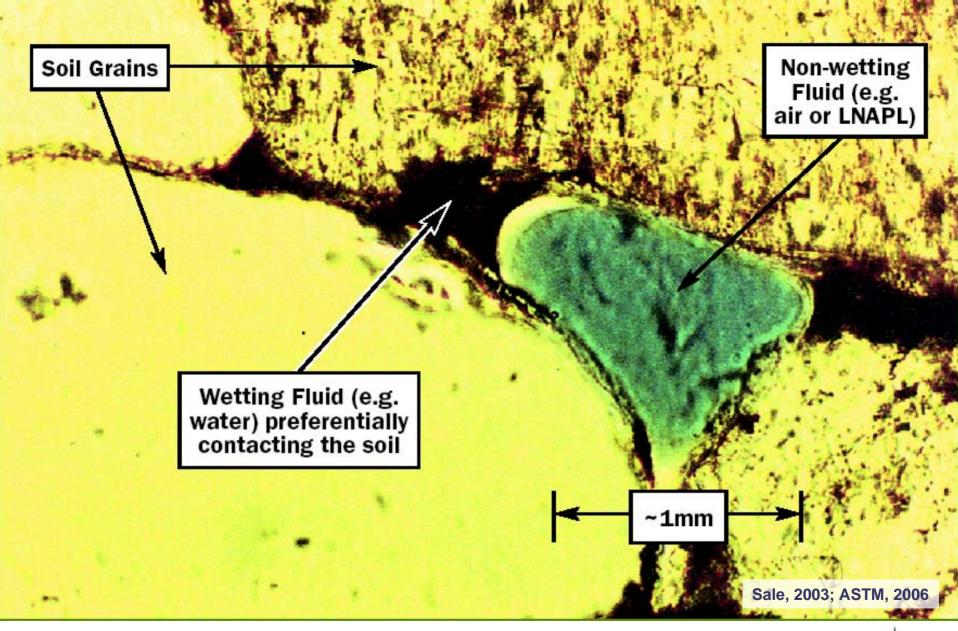


#### Groundwater there first...



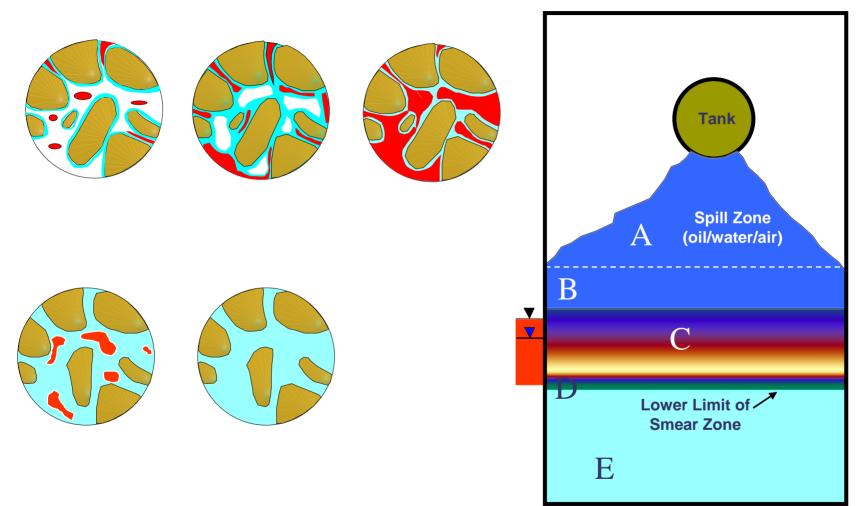
- LNAPL resisted by capillary entry pressure
- LNAPL must displace water from water-filled porosity before it can enter the pore



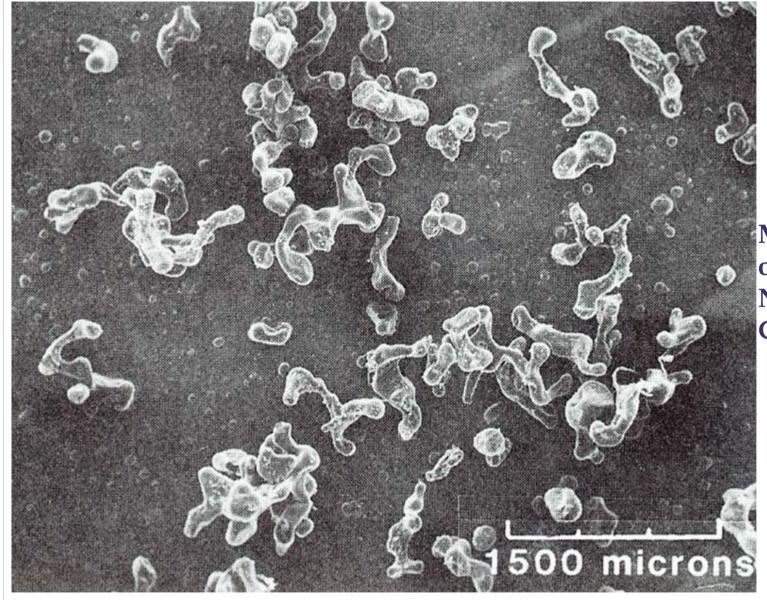




#### Schematic of LNAPL Source Distribution

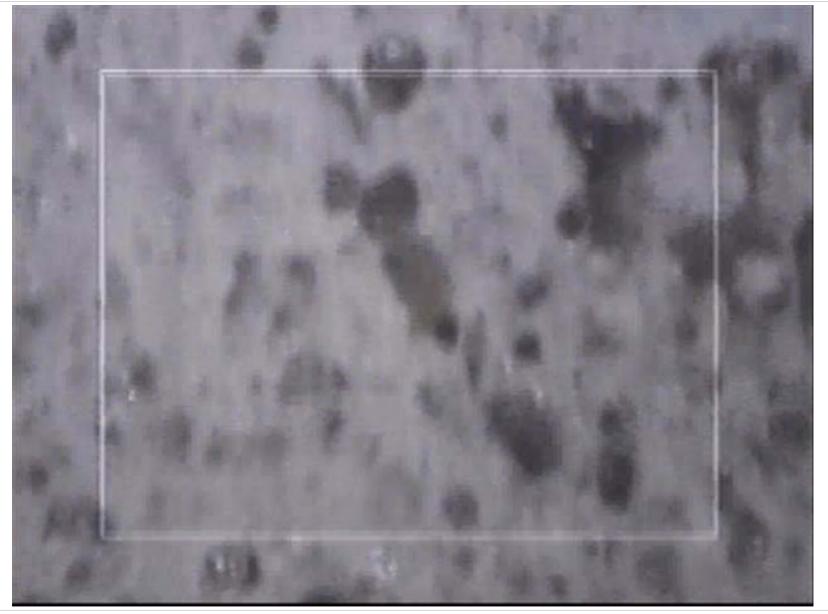






Micrograph of Residual NAPL Ganglia





Source: Beckett 2003



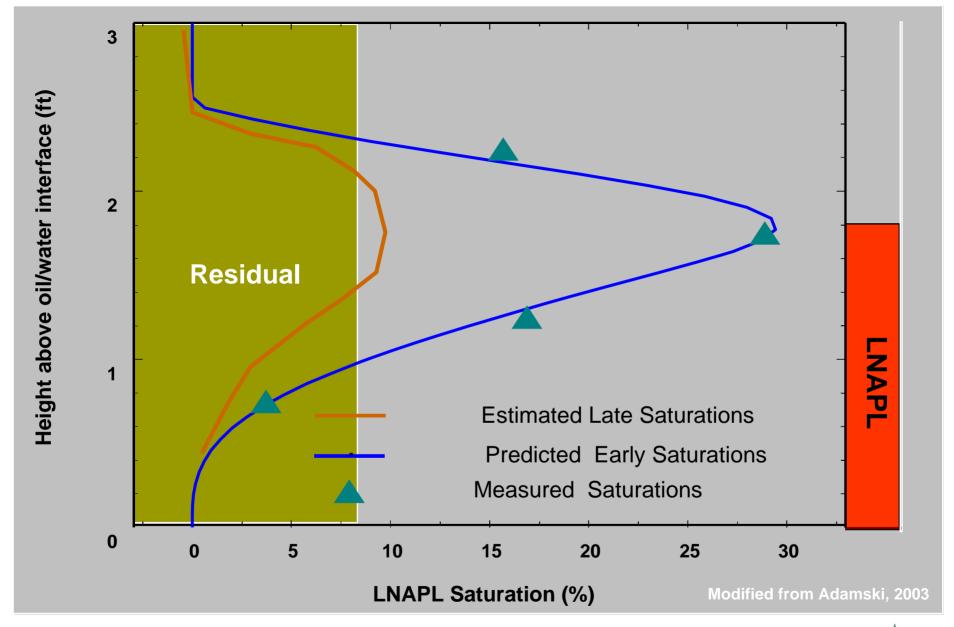
#### Saturation by Soil Type from 302 LNAPL Sites

As expected higher saturations in coarse grained soil, but lower than 100%

Soil Type	CL	ML	SC	SM	SW-SM	SW
Total # of Samples	73	46.0	21	43	22	54
Max LNAPL Saturation %	9.3	36.4	20.1	30.8	29.6	56.5
Average Saturation %	2.3	6.1	5.9	4.6	7.4	8.0
Max. Well LNAPL Thick.	15.3	7.2	7.5	8.3	8.3	2.4
Ave. Well LNAPL Thick.	6.2	3.0	4.1	2.8	5.8	0.8
# of Samples > 20% (10% for CL)	0	4	1	3	2	5
# of Samples > 10% (5% for CL)	11	10	6	8	6	14
% > 20% Saturation (10% for CL)	0.0%	8.7%	4.8%	7.0%	9.1%	9.3%
% > 10% Saturation (5% for CL)	15.1%	21.7%	28.6%	18.6%	27.3%	25.9%

(Adamski, 2006)







#### Demonstrate LNAPL Stability

- Effective hydraulic conductivity of LNAPL
  - "An absolute endpoint of LNAPL movement is when the LNAPL reaches field residual saturation, a condition where effective hydraulic conductivity of the LNAPL is zero." (Huntley and Beckett, 2001)
  - "LNAPL immobility occurs at an effective hydraulic conductivity below 10<sup>-6</sup> cm/s." (Brost and Beckett, 2000)
- Demonstrate that LNAPL effective hydraulic conductivity is less than 10<sup>-6</sup> cm/s.



#### LNAPL Effective Hydraulic Conductivity

$$K_{oil} = k_{ro} \frac{k_{soil} \rho_{oil} g}{\mu_{oil}}$$

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K_{oil} = effective LNAPL hydraulic conductivity in the soil
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 $k_{ro}$  = effective LNAPL-layer relative permeability (API model)

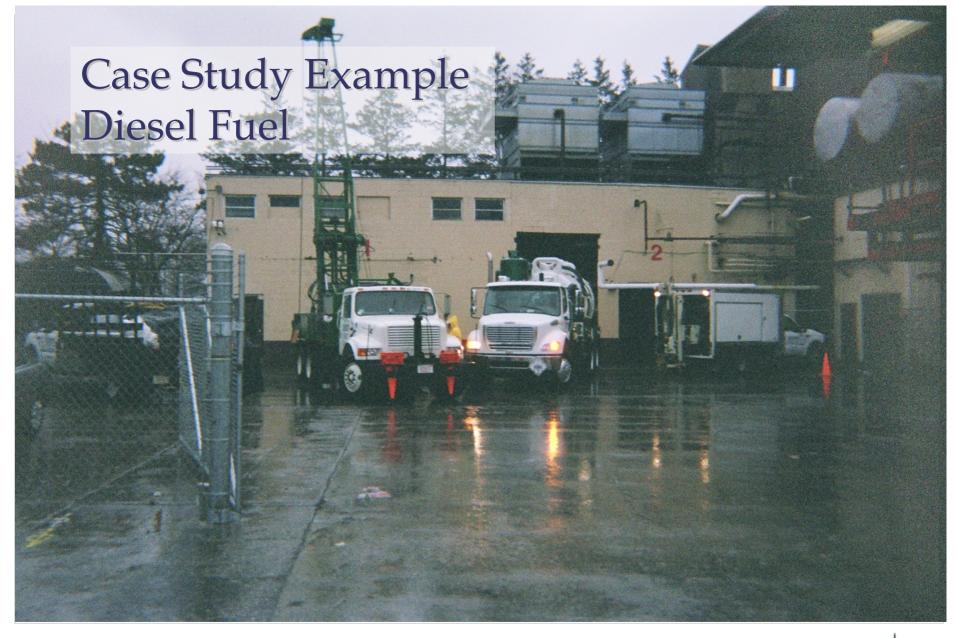
 $k_{soil}$  = permeability of soil

 $\mu_{oil}$  = dynamic viscosity of LNAPL

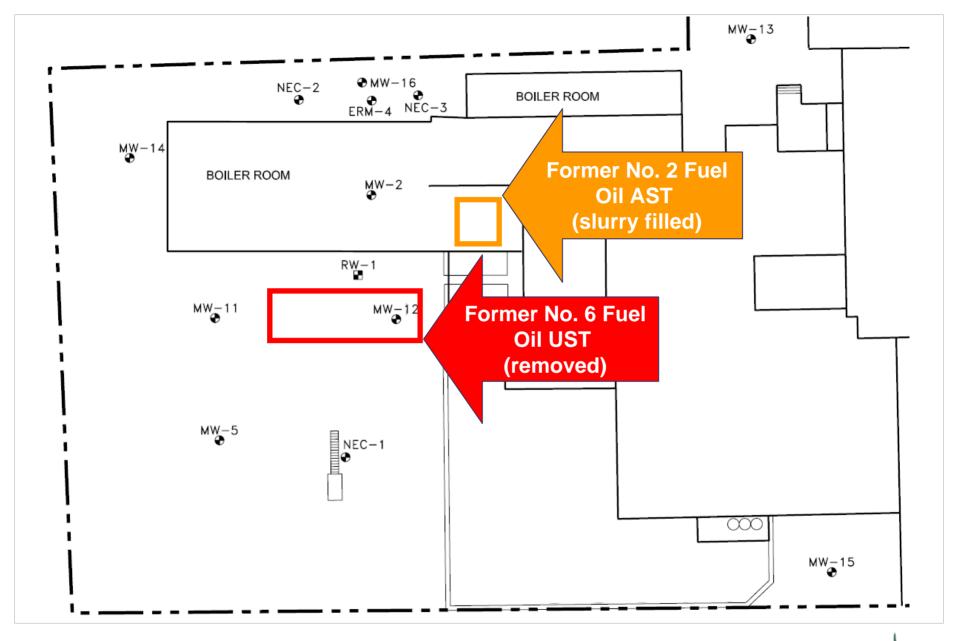
 $p_{oil}$  = density of LNAPL

*g* = gravitational acceleration

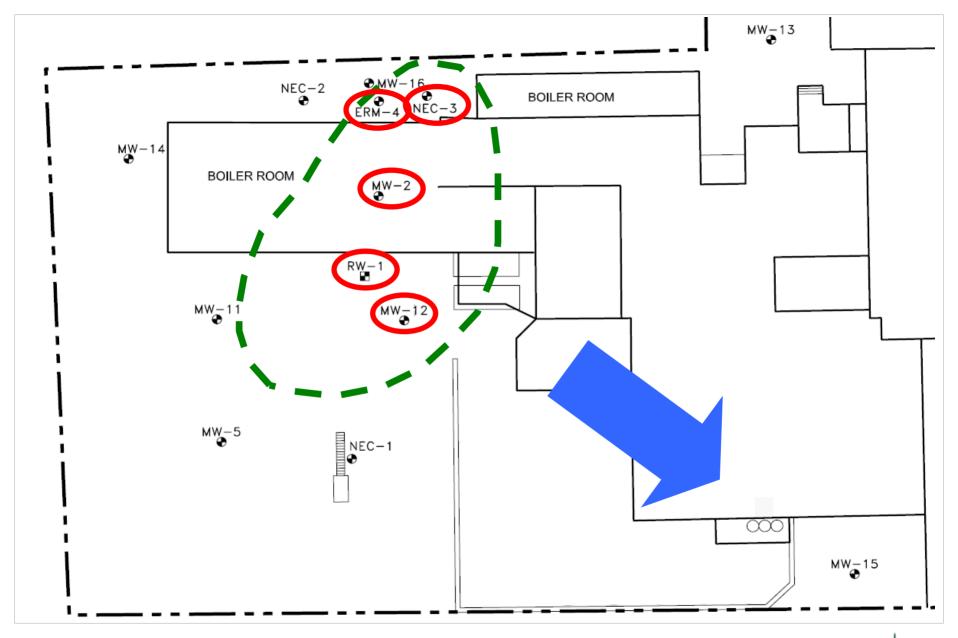




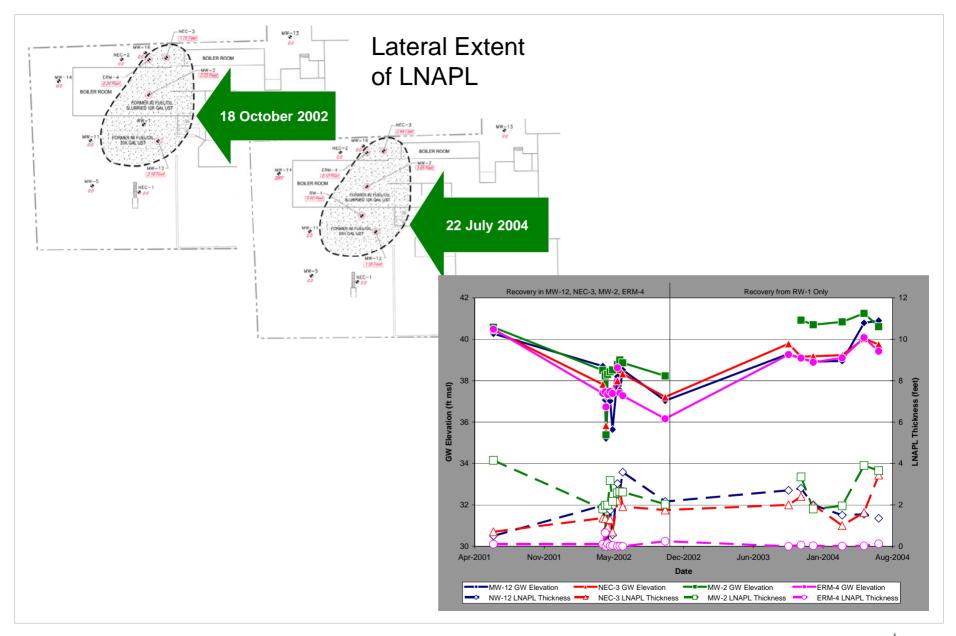














							RJC (8/14/98
Brooks-Core	ey LNAPL D	istribution Worksheet					
Enter Data in	Yellow Regi	on - Use Consistent Length Units					
		T	-				
Monitoring We	II Thickness 4.150	(longth)					
D <sub>0</sub> =	4.100	(length)					
Soil Character	istic	1	Copy data for V	Vork Chart	1		
n =	0.430	porosity	b <sub>o</sub> =	4.150	monitoring well thickness in computation		putation
λ =	1.130	pore size dist. Index	D <sub>o</sub> =	0.732	formation free-product volume (length)		
$\Psi_{baw}$ =	0.148	displacement pressure head (length)	<u>S</u> <sub>o</sub> =	0.410	effective LNAPL layer saturation		
S <sub>wr</sub> =	0.105	irreducible water saturation	<u>k</u> ro =	0.223	effective LNAPL layer rel. permeability		
S <sub>ors</sub> =	0.000	residual LNAPL saturation (saturated)	•		-		
S <sub>orv</sub> =	0.000	residual LNAPL saturation (vadose)	ε =	4.770			
S <sub>or</sub> =	0.000	resid. LNAPL sat. (rel. perm. calc.)	z <sub>ao</sub> =	0.256			
Z <sub>orv</sub> =	0.000	elev. vadose zone residual (length)	z <sub>ow</sub> =	-3.894			
$Z_{ors} =$	0.000	elev. saturated zone residual (length)	$z_r =$	0.503	van Genuchten Parameters		
Fluid Characte	ristics:		$\Psi_{bao}$ =	0.058	M =	0.628	
ρ <sub>o</sub> =	0.938	LNAPL density (g/cm³)	Ψ <sub>bow</sub> =	1.023	N =	2.690	
$\sigma_{aw} =$	74.100	air/water surface tension (dyne/cm)	ΔΨ =	0.966	α =	4.406	
$\sigma_{ow} =$	31.650	LNAPL/water surface tension (dyne/cm)	$z_{ao}+\Psi_{bao}=$	0.313	α <sub>ao</sub> =	11.292	
σ <sub>ao</sub> =	27.130	air/LNAPL surface tension (dyne/cm)	$z_{ow} + \Psi_{bow} =$	-2.871	$\alpha_{ow} =$	0.635	

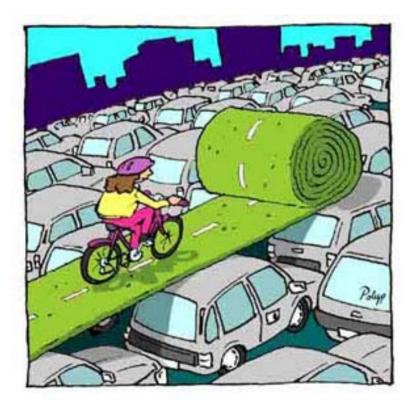
- Effective LNAPL hydraulic conductivity
  - ~10<sup>-7</sup> cm/s to ~10<sup>-9</sup> cm/s
  - Less than 10<sup>-6</sup> cm/s
- Results supported hypothesis that LNAPL body was stable and immobile







#### Path Forward



(Source: http://www.global-greenhouse-warming.com/global-warming-and-sustainability.html)

- Strong LNAPL
  Conceptual Site Model
- Most important for remediation decisions
- Main driver in this decision is risk reduction
- But in a sustainable frame of mind



## Summary

- As an industry we need to consider treating these types of minor layers of LNAPL as non-risk
- Incorporate sustainability in the remedy selection at all stages of the remedy
- Weigh not only financial, but also social and environmental aspects
- Begins with a better understanding of the source, and the LNAPL Conceptual Site Model





